Investigation of the magnetic and temperature sensitivity of the Stokes parameters of absorption lines in the solar photosphere

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Abstract

Response functions to perturbations in the temperature, pressure, microturbulent velocity, and magnetic intensity were calculated for the Stokes parameter profiles of the lines Fe I 525.06, 525.02 and Fe II 614.92 nm. The procedure proposed by Grossmann-Doerth, Larsson, and Solanki (1988) was used. We show that the depression response functions may be used not only to determine the depths at which changes in the physical conditions affect most effectively the absorption and emission in the continuum and in lines, but to estimate the response of Stokes profiles as well. The response was estimated using sensitivity indicators calculated as an integral of the response function over all photospheric layers. An anomalous temperature sensitivity was found for the Stokes profiles in lines with high excitation and ionization potentials such as the lines of O I, C I, Fe II. The depression of such lines increases rather than decreases with growing temperature. The magnetic sensitivity of Stokes profiles depends primarily on the magnetic field conditions. The response of V profiles is the greatest under the weak-field and intermediate-field conditions for photospheric lines with large values of the Landé factor, wavelength, and equivalent width. The results of calculations of sensitivity indicators are presented for magnetic lines together with the indices of magnetic and temperature enhancement.

1 Introduction

Small-scale features often called magnetic elements or magnetic tubes have a profound impact on the structure of the solar atmosphere. The magnetic tubes are supposed to be involved in the energy transfer to the upper chromospheric layers and corona, to affect the solar global magnetic fields and dynamo, to change the solar convection characteristics, etc. Much effort has been directed in the last decades toward thorough studies of their structure (see reviews of these numerous studies in [11, 14]). Small-scale structures are difficult to study, as they are not spatially resolved by present-day instruments. Their dimensions at the level where photospheric lines are formed are no more than 200 km, and magnetic intensity is more than 0.1 T. Evidence for their existence and main data on them are obtained from the Zeeman effect manifestations observed in atomic absorption lines which form in the photospheric regions with strong magnetic fields. Just the observed profiles of the Stokes parameters I, Q, U, and V for absorption lines provide the most

comprehensive information on the layer structure. They are a powerful diagnostic tool in constructing models of photospheric magnetic elements. As a rule, the Stokes V profiles are primarily used to determine the magnetic intensity, temperature, and velocity field inside magnetic tubes; these profiles describe the circularly polarized radiation emerging in absorption lines. Calculations are compared with such observed parameters of the Stokes V profiles as the maximum amplitudes and distances between them, half-widths, asymmetry of amplitudes and areas, zero-crossing wavelength. Pairs of lines are often used to find the ratios of maximum amplitudes and areas for the V profiles of two lines with different sensitivity to desired parameters of magnetic tubes. In investigations of this kind, especially in those using line pairs, it is important to select spectral lines in such a way that photospheric magnetic tubes might be explored at different heights and physical conditions might be determined the most exactly. It is rather difficult to select lines properly. In this paper we propose to do this selection using the sensitivity indicators which we derived based on response functions for radiation polarized in a magnetic field.

The first chapter contains the results of our calculations of response functions for the Stokes profiles of photospheric lines, and the second chapter presents the calculations of magnetic and temperature sensitivity indicators for the Stokes profiles.

2 Response functions

When fine effects are studied in the spectral analysis of absorption line profiles, the contribution and response functions are used, since only these functions allow us to find reliably the depths of absorption line formation. The contribution functions for the Stokes profiles were investigated quite comprehensively by Grossmann-Doerth et al. [2], Ress et al. [6], Solanki et al. [12], and in our paper [8]. The number of studies dealing with the response functions for the Stokes parameters is not large, they still are waiting for their thorough investigation, which may be explained by complexity of calculations. In 1977 Landi Degl'Innocenti with coauthors [4] introduced the concept of response functions for the Stokes parameters, regarding them as a convenient tool for the diagnostics of velocity fields and magnetic inhomogeneities in the atmospheres where spectral lines are formed. The method of atmosphere diagnostics with response functions was further elaborated in [5]. Grossman-Doerth et al. [2] generalized the response functions derived by Caccin et al. [1] for photospheric lines to the case with an arbitrary magnetic field and obtained handy response function expressions for both emission and depression in four Stokes parameters. We used these expressions to develop an algorithm for calculating the response functions of the Stokes parameters for photospheric absorption lines. A detailed description of the algorithm and calculation program is available in paper [7]. Here we give only the principal expression for a response function of a relative depression in a polarized radiation in an absorption line (it is called a depression response function) in the matrix representation:

$$\mathbf{RF}_\beta = \beta \mathbf{T}^{-1} \left[\frac{\delta \mathbf{F}}{\delta \beta} - \frac{1}{\kappa_c} \frac{\delta \kappa_c}{\delta \beta} (\mathbf{AR} + \mathbf{RA}^* - \mathbf{F}) - \frac{\delta \mathbf{A}}{\delta \beta} \mathbf{R} - \mathbf{R} \frac{\delta \mathbf{A}^*}{\delta \beta} \right] (\mathbf{T}^*)^{-1}.$$

Here β is a photospheric parameter which experiences small disturbances ($\delta\beta/\beta \ll 1$); $\mathbf{R}$ is the matrix describing a relative depression of polarized radiation in the line (line depth),

$$\mathbf{R} = \frac{1}{2} \left| \begin{matrix} RI + RQ & RU + iRV \\ RU - iRV & RI - RQ \end{matrix} \right|,$$

Table 1. Lines used in the analysis

Element	λ, nm	χ_e, eV	$\log gf$	R	W, pm	g_{eff}
Fe I	525.02	0.12	-4.89	0.71	6.5	3.0
Fe I	525.06	2.20	-2.06	0.79	10.3	1.5
Fe II	614.92	3.89	-2.85	0.34	4.0	1.3

where $RI = 1 - I/I_c$, $RQ = -Q/I_c$, $RU = -U/I_c$, $RV = -V/I_c$ are the Stokes parameters in relative depression units (by analogy with the line depth, they may be called the Stokes parameter depths). The classical Stokes parameters I, Q, U, V represent the intensity of the polarized radiation emerging in the spectral line; I_c is the continuum intensity; $\mathbf{A}$ is the matrix describing the polarization, absorption, and dispersion properties of the spectral line and the medium; $\mathbf{F}$ is the source function matrix; $\mathbf{T}$ is the matrix from the additional equation $d\mathbf{T}/d\tau = \mathbf{AT}$; κ_c is the continuous absorption coefficient.

Response functions for each individual Stokes profile are calculated from the following relations for the elements of the matrix $\mathbf{RF}_\beta$:

$$RF_{\beta,RI} = RF_{\beta,11} + RF_{\beta,22},$$
$$RF_{\beta,RQ} = RF_{\beta,11} - RF_{\beta,22},$$
$$RF_{\beta,RU} = RF_{\beta,12} + RF_{\beta,21},$$
$$RF_{\beta,RV} = (RF_{\beta,12} - RF_{\beta,21})(-i).$$

Generally the depression response functions characterize an additional contribution from each atmospheric layer to the line depression. This contribution is associated with those changes in absorption and emission in the line or in the continuum which result from a disturbance in one of atmospheric parameters. The depression response functions for the Stokes profiles describe an additional depression (response) in the polarized radiation in the given absorption line. Response functions depend on the kind of disturbance, line profile section, and height of the atmospheric layer. It should be noted also that the approximate equality

$$\mathbf{RF}_\beta(\Delta\lambda, x) \approx \Delta\mathbf{R}(\Delta\lambda, x)/(\Delta\beta/\beta(x))$$

is true for a response function in a thin layer at the height $x = \log \tau_5$.

The response function may be used to estimate variations in the relative depression of the emerging polarized radiation in the line ($\Delta\mathbf{R}$) caused by the disturbance $\Delta\beta/\beta$ when the disturbance is substantially less than unity:

$$\Delta\mathbf{R}(0) = \int \mathbf{RF}_\beta \frac{\Delta\beta}{\beta} d\tau.$$

Numerical calculations of the response functions for the Stokes parameters were made with the SPANSATM program [7] for the HOLMU model photosphere with a magnetic intensity $H = 0.2$ T, an angle of inclination $\gamma = 30°$, an azimuth $\phi = 30°$, and $\xi_{\text{mic}} = 0.8$ km/s, $\gamma_{\text{VdW}} = 1.3\gamma_6$. The macroturbulent velocity does not appear in the calculations of the absorption coefficient, and we neglected it in our response function calculations. Spectral lines were selected so that their response to magnetic field effects might be different as much as possible. The parameters of these lines are given in Table 1. Central depths R and equivalent widths W are taken from observations of the quiet Sun. The iron abundance is 7.64.

Figure 1 shows the difference between the Stokes profiles calculated for the lines for which response functions will be found. Profiles of the V parameter are most often used in
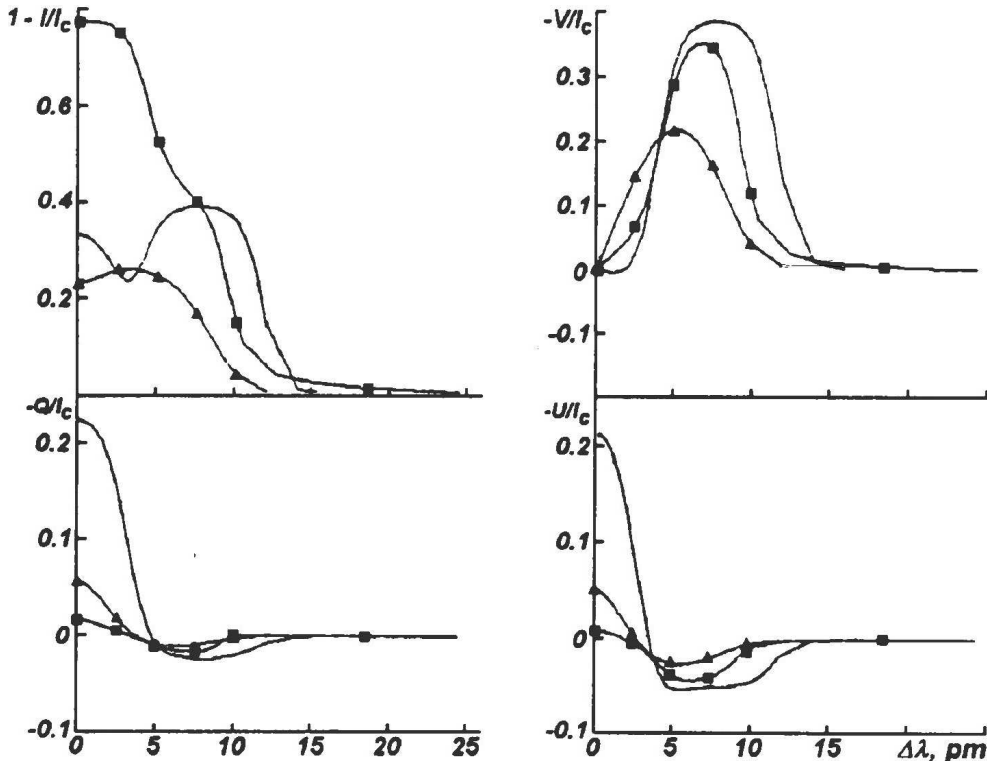
Fig. 1. The Stokes profiles for the lines Fe I 525.02 nm (lines), 525.06 nm (lines and squares), and Fe II 614.92 nm (lines and triangles) calculated with the HOLMU model solar photosphere and a magnetic field of intensity $H = 0.2$ T, $\gamma = 30°$, $\phi = 30°$.

the spectral analysis of the Stokes profiles in observations as well as in modeling magnetic elements. Therefore we center our attention on the properties of response functions of V profiles in our analysis of the response to changes in the temperature, pressure, micro-turbulent velocity, and magnetic intensity. Figures 2 and 3 show the most representative response functions selected from the results of calculations. The body of data being too great, we restrict ourselves only to the response functions for the profile section lying at the distance $\Delta\lambda$ where the V profile attains its maximum, i.e., for $\Delta\lambda(RV_{\max})$.

2.1   Response functions to temperature variations

Figure 2, on the lower left, depicts the response of V profiles to temperature variations. The magnitude of response changes from layer to layer as evidenced by the shape of the curve describing the response function. The calculations suggest that the shape of the curve may change from a simple one (nearly Gaussian) to a complex one with two maxima of different heights. The greater maximum characterizes the contribution to the V profile depression of an additional depression produced by radiative processes in the line, while the smaller maximum at $\tau \approx 1$ is due to radiative processes in the continuum. Comparing response functions for different lines, one can note that the height of the greater maximum or the integral value of the function are distinctly different. They may take both positive and negative signs. The negative value of the response function means that the depression $RV_{\max}$ decreases when the temperature grows by ΔT, and the positive value means that $RV_{\max}$ increases. The integral value of the functions, which determines the quantity $\Delta RV(0)$, is always negative for lines with a very small effective excitation potential χ_* (low excitation potential plus ionization potential), it approaches zero with
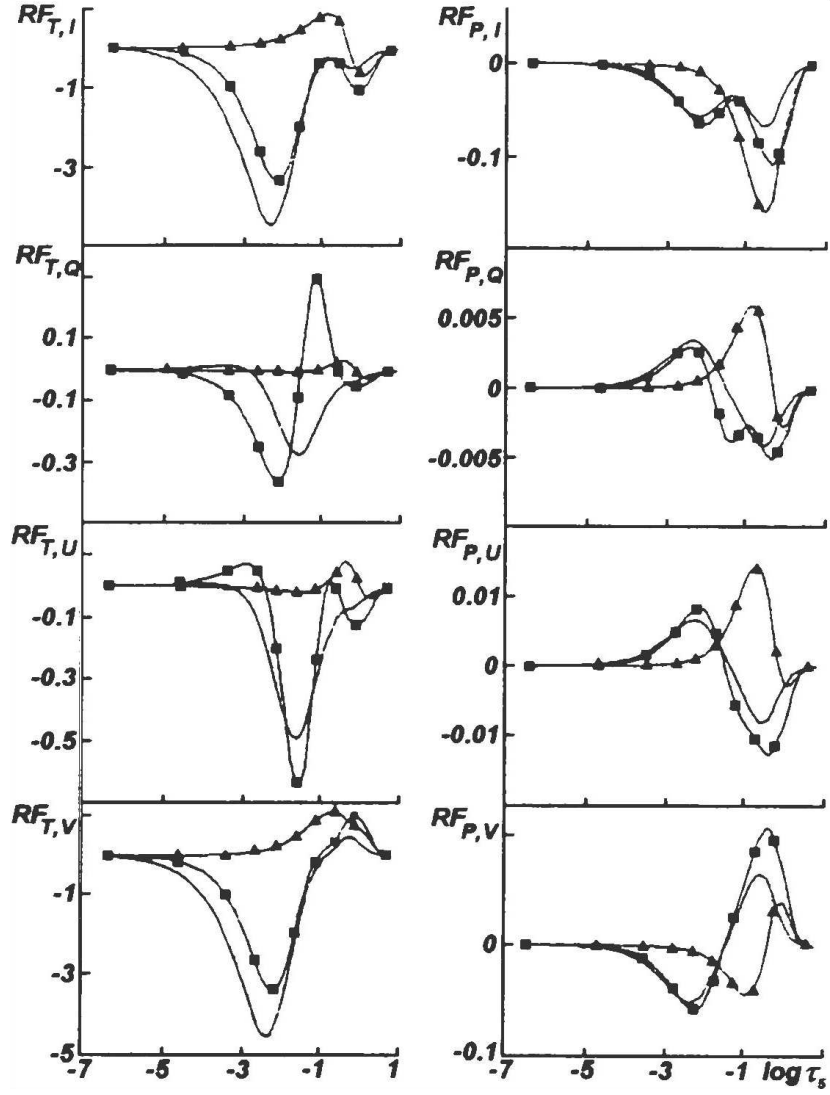
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Fig. 2. Response functions for the Stokes profiles shown in Fig. 1, for the profile section at the distance $\Delta\lambda = \Delta\lambda(RV_{\max})$. On the left) response to temperature, on the right) response to pressure. Marking is the same as in Fig. 1.

growing χ_* and then increases again and becomes positive, remaining small. In practice this suggests that in lines with high χ_* (the lines of iron ions and carbon) the observed values of RV and RI may somewhat grow rather than decrease in the regions with an increased temperature (plages), while they may become smaller in regions with a decreased temperature (sunspots). Certainly, this reverse effect is small, and these lines have a low sensitivity to temperature. Nevertheless this peculiarity allows the efficiency of V profile observations to be higher when lines with anomalous temperature sensitivity are selected.

The response functions for I profiles (Fig. 2, on the upper left) differ from the V profile functions discussed above by the sign of the smaller maximum. This may reflect on the integral sensitivity of I and V profiles. The general additional negative depression in I profiles will be greater than in V profiles while the positive depression will be smaller. The functions for Q and I profiles have more complex shapes, and the maxima in them are smaller. In their general outline, the response functions for I profiles are nevertheless closer to the V-profile functions. When the magnetic vector inclination is small (it is 30° in our specific example), RQ and RU are small in magnitude at the distance $\Delta\lambda(RV_{\max})$ from the

5

line center, and therefore their contribution to the general depression RI is small. Thus one can well understand why the function for RI, which represents the general depression response, resembles the function for V profiles.

2.2 Response functions to variations in pressure

The response of Stokes profiles to changes in pressure is much weaker than the response to temperature variations. The functions of response to pressure fluctuations are plotted at the right of Fig. 2. In these functions for V profiles the additional depression due to processes in the continuum is greater in magnitude than the depression due to processes in the line, i.e., the second maximum is greater in deep layers than the first one. Interestingly, there are essential differences between the response functions for I and V profiles. For instance, the integral response for the ion line is almost zero in the V profile, while in the I profile it is the greatest as compared to the other lines. As the pressure increases, the greatest response in V profiles is found in broad lines rather than in lines with large χ_*.

2.3 Response functions to variations in the microturbulent velocity

A distinguishing feature of these functions is their less intricate shape (Fig. 3, at the right). They have a well-defined maximum. This is a consequence of the fact that disturbances in the velocity field parameters and in the magnetic field do not affect the processes in the continuum, and therefore there is no maximum in the deep layers. The response functions for I and V profiles are similar. The amplitude of V profiles may diminish with increasing ξ_{mic} when the line half-width is less than $\Delta\lambda_H$, and it may grow when the half-width is greater than $\Delta\lambda_H$. The integral response is the greatest in lines with a half-width greater than $\Delta\lambda_H$. The maximum response to ξ_{mic} is nearly to the maximum response to P_g.

2.4 Response functions to variations in the magnetic intensity

These functions resemble in their shape the response functions for velocity variations and differ sometimes in their sign (Fig. 3, at the left). The response functions for I and V profiles are also similar. They are only positive, which testifies that the depression in I and V profiles grows on the section corresponding to the maximum value of RV when the magnetic intensity H increases by ΔH. The greatest response is found in the broad line with the half-width $\geq \Delta\lambda_H$. The maximum response to changes in the magnetic intensity is smaller in magnitude than the response to temperature and is slightly greater than the response to pressure and microturbulence.

2.5 Discussion on the response functions for the Stokes parameters

Thus the depression response functions for the Stokes parameters of iron lines allow us to analyze the sensitivity of profiles to structural inhomogeneities. Among the atmospheric parameters such as the temperature, pressure, microturbulent velocity, and magnetic intensity which govern the Stokes profiles, it is precisely the temperature disturbances that produce the strongest response. The response to temperature variations estimated by either the function's maximum value or its integral value may exceed the response to magnetic intensity disturbance by a factor about 3 and the response to pressure and velocity by
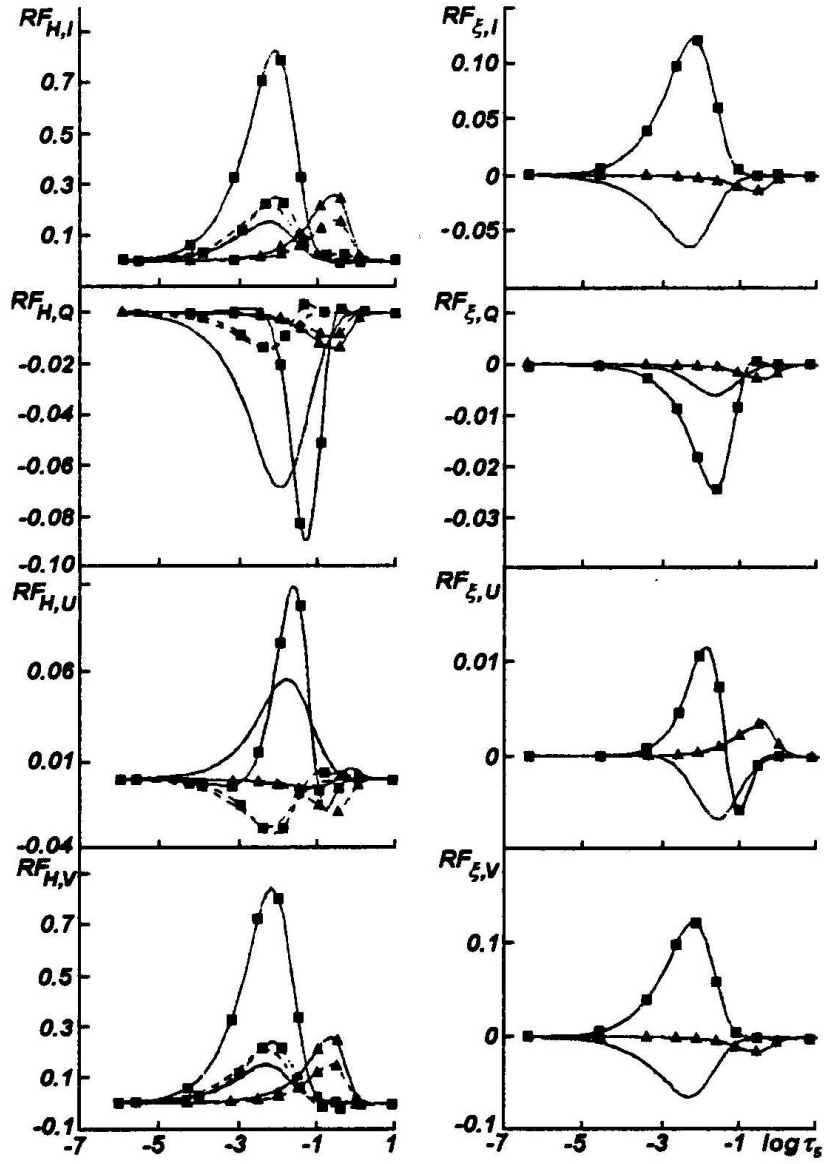
Fig. 3. The same as in Fig. 2. On the left) response to magnetic intensity, on the right) response to microturbulent velocity. Dashed lines are depression contribution functions.

a factor about 10. Hence it follows that the temperature sensitivity should be checked first when we determine the magnetic sensitivity of Stokes parameters, and only afterwards, if the line is broad, the sensitivity to velocities and pressure should be checked.

The dependence of the temperature sensitivity of absorption line profiles on the low excitation potential and ionization potential which was shown to exist in [9] is confirmed for the Stokes profiles as well. The most sensitive to temperature are the V profiles of lines with low values of the excitation and ionization potentials. Their amplitude diminishes with growing temperature. The temperature sensitivity of the V profiles for lines with high values of the excitation potential diminishes, becomes zero, and may even become anomalous, i.e., it grows again but with the opposite sign for very high potentials. The V profile amplitude grows in this case. An increase in temperature in the region of absorption line formation diminishes the maximum amplitude of V profiles for the lines of Fe I, Ti I, Co I, Sc I, V I, Cr I, Cu I, Ni I, leaves it virtually unchanged for the Si I, Zn I lines, and increases it slightly for the lines of C I, 0 I, Fe II, etc. The magnetic sensitivity of the

Stokes V profiles depends largely on the ratio between the line half-width and the width of the Zeeman splitting (the same is true for the sensitivity to pressure and velocities). When the half-width is close to or greater than the Zeeman splitting, the maximum and the area of the response function increase abruptly, and this means that the magnetic sensitivity increases. Hence it follows that the line magnetic sensitivity depends on the magnetic field conditions and it cannot be forecast accurately based only on the atomic parameters of the line.

The depression response functions are useful also in finding the depths at which the action of the magnetic field on different sections in the Stokes profiles of spectral lines is the most effective. The dashed lines in Fig. 3 show for comparison the depression response functions for I and V profiles which are recommended in [8] to be used for calculating the depths of formation of the Stokes profiles. These functions are seen to point to the same depth region in the photosphere. However, the calculation of response functions being substantially more complicated, the contribution functions are likely to be more adequate for determining the depths of formation.

Thus, the response functions, when used in the spectral analysis of the radiation polarized in a magnetic field, provide a way for estimating the response of the Stokes profiles to disturbances of physical conditions in a medium in all layers in the region where the line is formed; the depths in the atmosphere at which the disturbance changes the profiles most strongly can be appreciated also. To determine the sensitivity of the profiles of magnetic lines, we may use estimates of the response of Stokes profiles to changes in atmospheric parameters. We discuss this problem in the following section.

3 Sensitivity indicators and indices of magnetic and temperature enhancement

In order to determine, for example, the magnetic sensitivity of a line, which depends not only on the Landé factor but on the magnetic saturation of the line and its temperature sensitivity as well, and this was clearly demonstrated in [13] by the example of the Stokes V profiles observed in different lines, we need to know all responses to changes in the physical conditions. We have a possibility to analyze quantitatively the magnetic sensitivity of Stokes parameters using the response functions which allow us to study separately the effect of physical parameters on the amplitude, area, any section of the Stokes profile. The integral response function, which yields the net response to a disturbance of all photospheric layers where the absorption line is formed, may serve as quantitative measure of the magnetic sensitivity; we call this measure the sensitivity index or indicator for the Stokes parameters.

For the V profile, the indicator of sensitivity to the magnetic intensity H (we denote it by $P_{H,V}$) on the profile section $\Delta\lambda$ is equal to the integral of the corresponding depression response function $RF_{H,V}$ for the Stokes parameter V over all layers $x = \log \tau_5$:

$$P_{H,V}(\Delta\lambda) = \int_{-\infty}^{\infty} RF_{H,V}(x, \Delta\lambda)dx.$$

The sensitivity index calculated in this way is the rate of variation in the depression $RV(0, \Delta\lambda)$ emerging at the surface as related to the relative rate of variation in the disturbed atmospheric parameter H. When we want to obtain the index in the relative depression units, $P_{H,V}$ should be divided by the relative depression $RV = -V/I_c$ of the
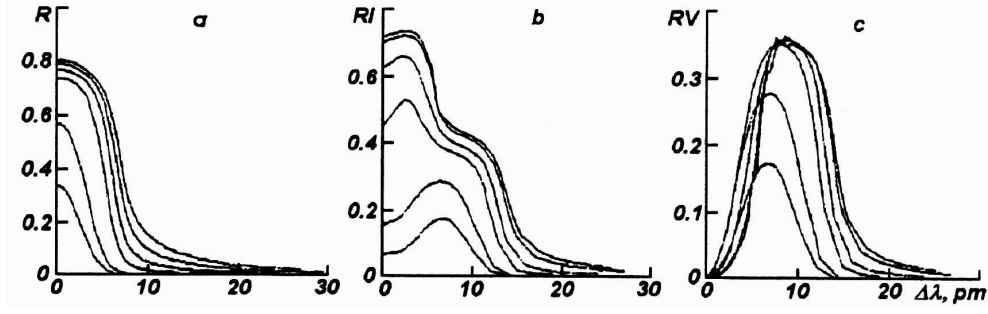
Fig. 4. Profiles of the hypothetical lines Fe I 600.0 nm, $\chi_e = 2$ eV, $g_{\text{eff}} = 2$ with $W = 2, 4, 8, 10, 12, 14$ pm calculated without a magnetic field (a) and the Stokes profiles RI (b) and RV (c) in the magnetic field with an intensity of 0.2 T, $\gamma = 30°$, $\phi = 30°$. HOLMU model photosphere.

Stokes parameter V. The sensitivity indices for other Stokes parameters are determined in the same way. The sensitivity indicator for the entire Stokes profile as a whole

$$PW_{H,V} = \int_{-\infty}^{\infty} RFW_{H,V}(x)dx$$

is calculated using the integral response function

$$RFW_{H,V}(x) = \int_{\text{line}} RF_{H,V}(x, \Delta\lambda)d(\Delta\lambda)$$

describing the net response of the whole profile. The increase in the equivalent width of a line due to magnetic field is called the magnetic line enhancement, and so the magnetic sensitivity indicator for the equivalent width of the Stokes parameter I specified by the integral

$$PW_{H,I} = \int_{-\infty}^{\infty} RFW_{H,I}(x)dx$$

is the index of the magnetic line enhancement. Recall that the approximate equality $\Delta W_I \approx PW_{H,I}(\Delta H/H)$ is valid when disturbances are sufficiently small ($\Delta H/H <\ll 1$), and it allows estimating the change in the magnetic field $\Delta H/H$ in the region of line formation if ΔW_I, is known from observations.

In calculating specific sensitivity indicators we used the same initial data as in the calculations of response functions. The calculations of sensitivity indicators for actual lines yielded results so varied that we could see no regularities at first glance. We had to change the calculation tactics. First we restricted our consideration to the sensitivity parameters for the V profiles and for the temperature and magnetic intensity only. The profiles Q and U are observed less accurately, as a rule, the ratio of their amplitudes to noise distortions being too small, and they are not practically used in the Stokes profile interpretations. Second, to find the dependence of the indicators on line atomic parameters and on conditions of line formation, we selected hypothetical lines of Fe I with the following parameters: $W = 2, 4, 8, 10, 12, 14$ pm; $\lambda = 450, 600, 750$ nm; excitation potentials $\chi_e = 0, 2, 4$ eV; the Landé factors $g_{\text{eff}} = 1, 2, 3$. The reference line had the parameters $W = 4$ pm, $\lambda = 600$ nm, $\chi_e = 2$ eV, $g_{\text{eff}} = 2$, $H = 0.2$ T, $\gamma = 30°$, $\phi = 30°$. Varying λ, g_{eff}, χ_e, W, and H one after another, we calculated the V profiles and their magnetic and temperature sensitivity. Figures 4–7 show the principal results.
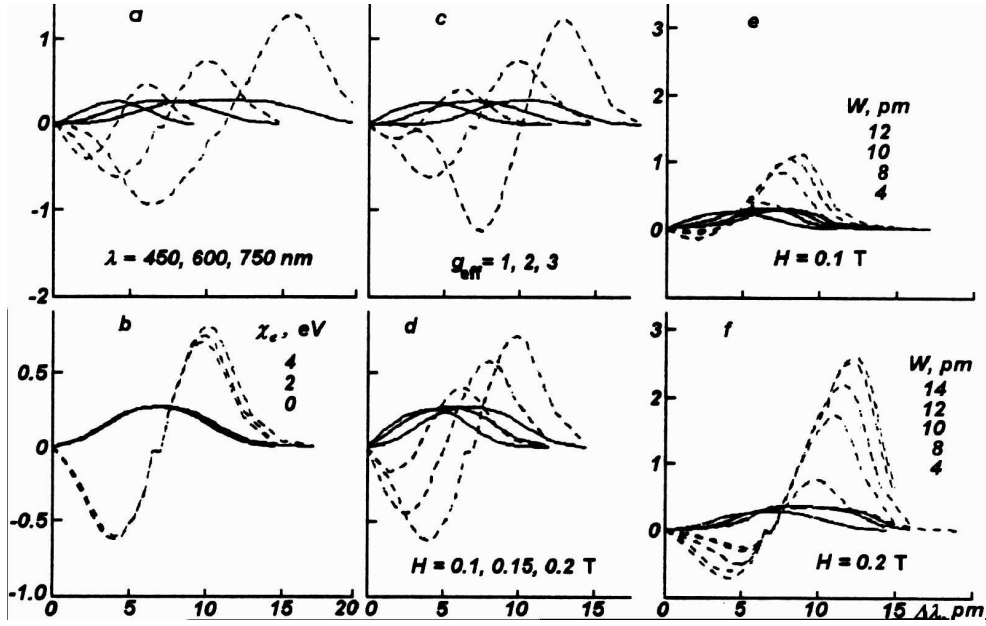
9

Fig. 5. Magnetic sensitivity profiles (dashed lines) calculated for the Stokes V profiles (solid lines) in the magnetic field with $H = 0.2$ T, $\gamma = 30°$, $\phi = 30°$: a) with different wavelengths and $\chi_e = 2$ eV, $g_{\text{eff}} = 2$, $W = 3, 4.4, 6.6$ pm; b) with different excitation potentials and $\lambda = 600$ nm, $\chi_e = 2$, $W = 4.4$ pm; c) with different Landé factors and $\lambda = 600$ nm, $\chi_e = 2$, $W = 4.4$ pm; d) with different magnetic intensities and $\lambda = 600$ nm, $\chi_e = 2$, $g_{\text{eff}} = 2$, $W = 4.4$ pm; e) with different equivalent widths and $\lambda = 600$ nm, $\chi_e = 2$, $g_{\text{eff}} = 2$, $H = 0.1$ T; f) the same as (e) but with $H = 0.2$ T.

4   Results and discussion

Figure 4a shows the profiles of the hypothetical lines with different equivalent widths. The profiles were calculated for the quiet Sun, i.e., without magnetic field. Figures 4b,c show the profiles of the Stokes parameters I and V only, in relative depression units, for the same lines ($RI = 1 - I/I_c$, $RV = -V/I_c$). Similar to an absorption line profile, the sensitivity profile $P_{H,V}(\Delta\lambda)$ can be calculated, it represents the dependence of sensitivity indicators on the distance $\Delta\lambda$ to the line center. The sensitivity profiles can be used for the analysis of the magnetic sensitivity of the Stokes V profiles. Figure 5 depicts V profiles (solid lines) and magnetic sensitivity profiles (dashed lines) as functions of the wavelength (a), low excitation potential (b), Landé factor (c) magnetic intensity (d), and equivalent width in a field with $H = 0.1$ T (e) and $H = 0.2$ T (f). The distinctive feature of the magnetic sensitivity profile is that it is a double-peaked curve with a positive and a negative maxima which accounts for actual variations in the Stokes V profile when the magnetic intensity H grows by ΔH. The V profile given by our calculations being antisymmetric, we consider here only its red wing which, in its turn, also has two wings. The left wing in the V profile is always matched by a negative peak in the sensitivity profile, and this means that RV decreases due to its shift resulting from an increase in H. The right wing is matched by a positive peak which characterizes the increase in RV in these line profile sections. The distance between the peaks characterizes the width of the red wing in the V profile. If lines have different excitation potentials and all other their parameters are close, the magnetic sensitivity profiles of these lines are virtually the same. The most interesting situation was observed for lines with different equivalent widths. For a specific

10

magnetic field, 0.2 T in this case (Fig. 5f), the positive peak in the sensitivity profile rapidly increases and becomes dominant when W increases and other line parameters, apart from gf, remain unchanged. At the same time the negative peak grows first until $W = 8$ pm and then it decreases and becomes much smaller than in weak lines. As the integral sensitivity rises sharply over the entire profile, $RV_{\max}$ also increases together with the V-profile area and the index of magnetic line enhancement. This increase stops in lines with $W > 12$ pm. Simple calculations reveal that the growth of magnetic sensitivity depends not so much on the equivalent width as on the radio between the line half-width (we denote it by $\Delta\lambda_D$) and the magnetic broadening ($\Delta\lambda_H$). The sensitivity of V profile grows abruptly when $\Delta\lambda_D \geq \Delta\lambda_H$. The ratio of these quantities is known to specify the magnetic field conditions under which the spectral line exists. The sensitivity indicators calculated by us suggest that the magnetic sensitivity of V profiles shows up in different ways depending on the field conditions. Solanki [10] describes the characteristic features of these field conditions with the magnetic sensitivity taken into account.

1) $\Delta\lambda_D \gg \Delta\lambda_H$, weak-field conditions. In this case the distance between the red and blue maxima in the V profile, $\Delta\lambda(V_{\max})$, depends on $\Delta\lambda_D$ only. The maximum amplitude is proportional to the magnetic intensity, $V_{\max} \approx H$ and $Q_{\max} \approx H^2$. Spectral lines are not splitted under these condition and I profiles provide information on the average field $<H>$ only. These lines can be used for measuring H only in the case when the field is spatially resolved or when there is a possibility to observe V profiles. The magnetic sensitivity of V profiles is high.

2) $\Delta\lambda_D \approx \Delta\lambda_H$, intermediate-field conditions. Here $\Delta\lambda(V_{\max})$ and $\Delta\lambda(Q_{\max})$ depend on both $\Delta\lambda_H$ and $\Delta\lambda_D$. The dependence of the maximum amplitudes $V_{\max}$ and $Q_{\max}$ on H is weaker than under the weak-field conditions. Lines are partially split, and H is measured in these conditions using such intricate methods for the analysis of Stokes profiles as the line ratio method, inversion methods, the Fourier transformation. The magnetic sensitivity of V profiles may vary in these conditions from moderate to high.

3) $\Delta\lambda_D \ll \Delta\lambda_H$, strong-field conditions. Spectral lines are completely splitted. Here $\Delta\lambda(V_{\max}) = \Delta\lambda(Q_{\max})$, $V_{\max}$ and $Q_{\max}$ are independent of H. The field intensity can be obtained easily from $\Delta\lambda(V_{\max})$ or $\Delta\lambda(Q_{\max})$. The magnetic sensitivity of V profiles is low.

All these conditions can be observed in Figs 5e,f, and the sensitivity of V profiles for different lines can be compared. Of the lines with $W = 4, 8, 10, 12, 14$ pm which have the half-widths $\Delta\lambda_D = 3.3, 5.2, 6.0, 6.7, 7.2$ pm, respectively, and a 6.7 pm magnetic broadening for $\lambda = 600$ nm, $g_{\text{eff}} = 2$ in the field $H = 0.2$ T (Fig. 5f), the lines with $W = 8, 10, 12, 14$ pm find themselves under the intermediate-field conditions, while lines with $W < 8$ pm are under the strong-field conditions. The weak-field conditions set in for lines with $W > 14$ pm. When $\Delta\lambda_H$ becomes smaller, for instance, the magnetic intensities reduced by one half, the magnetic sensitivity increases in lines with much smaller equivalent widths? This means that for lines with $\lambda = 600$ nm, $g_{\text{eff}} = 2$, $H = 0.1$ T, $\Delta\lambda_H = 3.3$ pm (Fig. 5e), the lines with $W = 4, 6, 8$ pm are in the intermediate-field conditions, lines with $W < 4$ pm are in the strong-field conditions, and lines with $W > 8$ pm are in the weak-field conditions. In going from a strong field to a weak one, the sensitivity of V profiles grows, reaches its peak and then remains practically unchanged. The same line (e.g., the line with $W = 10$ pm) is under the weak-field conditions in a field with $H = 0.1$ T and under the intermediate-field conditions at $H = 0.2$ T, but the sensitivity of its V profile is higher where the field is stronger. The sensitivity of lines may vary within the intermediate- and weak-field conditions owing to differences in individual line parameters.

The sensitivity of V profiles to magnetic field may become more pronounced if lines
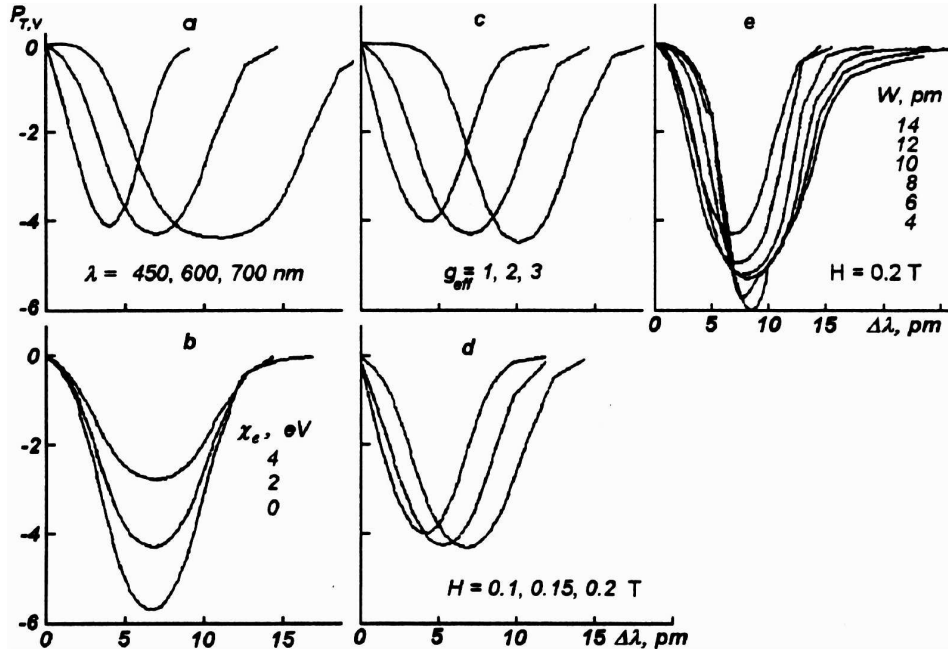
Fig. 6. Temperature sensitivity profiles calculated for the same Stokes V profiles as shown in Fig. 5.

insensitive to temperature are selected. We have already noted in the second section of this paper that the response of Stokes profiles to temperature variations is by an order of magnitude greater in the most sensitive lines than the response to magnetic intensity. The temperature strongly affects the equivalent width W and the line half-width $\Delta\lambda_D$. The latter quantity is proportional to $\lambda T^{1/2}$, line saturation, microturbulence and damping broadening. Changes in temperature can easily take the line from some conditions to other and can thus change the line sensitivity.

Figure 6 presents the temperature sensitivity profiles for the V profiles of hypothetical lines as functions of atom and medium parameters. The most temperature-sensitive are the V profiles of moderate photospheric lines (14 pm > W > 6 pm) with low values of excitation potential. The temperature sensitivity profiles for actual lines are shown in Fig. 7. Besides, Table 2 gives the results of calculations of sensitivity indicators for the maximum value of the V profile ($P_{H,V}$ and $P_{T,V}$) and for its area ($PW_{H,V}$ and $PW_{T,V}$) as well as the indices of magnetic enhancement $PW_{H,I}$ and temperature enhancement $PW_{T,I}$ in a field with $H = 0.2$ T, $\gamma = 30°$, $\phi = 30°$, and T(HOLMU) for spectral lines often used in spectropolarimetric observations. These quantitative estimates of the temperature and magnetic sensitivity can be relied on in a comparative analysis and in selecting lines for an investigation of the magnetic field structure in small-scale magnetic features at the photospheric level. To do this, we have to assess the changes in the maximum value of RV, in the V profile area W_V or in the line's equivalent width W_I, which would occur when the magnetic intensity increases, say, by 5% ($\Delta H = 0.01$ T, $H = 0.2$ T, $\Delta H/H = 0.05$) and the temperature increases by 2% ($\Delta T = 100$ K, $T = 5000$ K, $\Delta T/T = 0.02$) for the lines $\lambda\lambda$ 525.02, 525.06, and 614.92 nm. We find the sensitivity indicators in Table 2 and calculate $\Delta RV_{\max}$, ΔW_V, ΔW_I using the approximations of the type $\Delta W \approx PW_H \Delta H/H$. The results are given in Table 3.

The dependence of the sensitivity indicators for the Stokes profiles on various parameters of both the line and the medium being rather intricate, the sensitivity to magnetic field cannot be uniquely determined, i.e., we cannot find the magnetic sensitivity of V
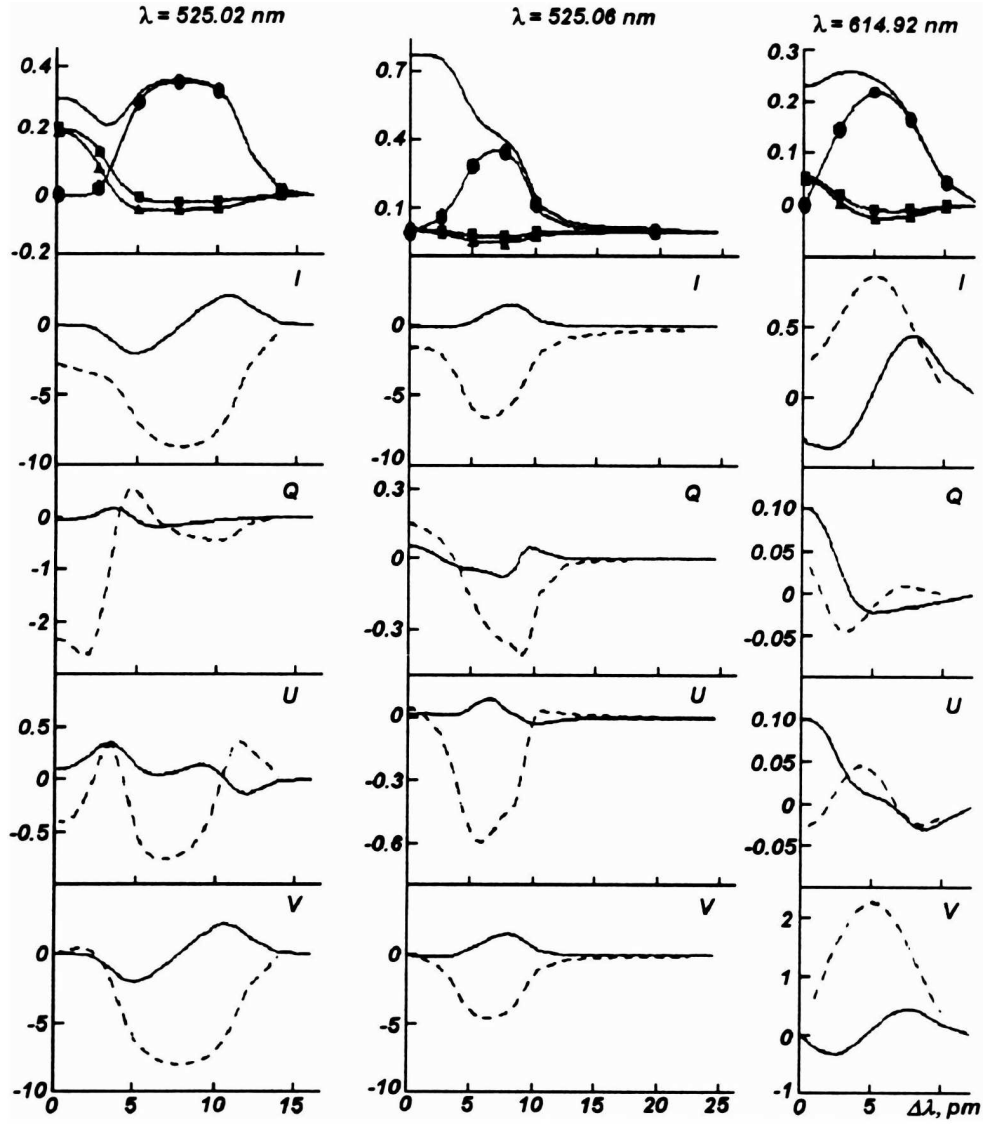
Fig. 7. Temperature (dashed lines) and magnetic (solid lines) sensitivity profiles for the profiles of Stokes parameters for three spectral lines Fe I 525.02, 525.06 nm, Fe II 614.92 nm in the magnetic field with $H = 0.2$ T, $\gamma = 30°$, $\phi = 30°$; at the top: solid lines) RI, squares) RQ, triangles) RU, dots) RV.

profiles, for instance, from such line parameters as λ, χ_e, R, W, g_{eff}. We have to know also the parameters H and T of the medium, i.e., the magnetic field conditions. To determine these conditions, we have to carry out the following procedure. We calculate the line half-width and magnetic broadening and compare them. Figure 8 depicts the plots of $\Delta\lambda(H)$ for different λ and g_{eff} and the plots of $\Delta\lambda_D(W)$ used for the assessment of conditions for the lines of neutral iron. The line half-width $\Delta\lambda_D$ can be estimated from these plots with the known λ and W. With the known λ, g_{eff} and H, we can find the magnetic broadening $\Delta\lambda_H$, compare it with $\Delta\lambda_D$, and thus determine the sensitivity of the V profile for any Fe I line in a medium with the H and T(HOLMU) chosen.

13

Table 2. Magnetic and temperature sensitivity indicators. W_V, W_I, $PW_{H,V}$, $PW_{T,V}$, $PW_{H,I}$, $PW_{T,I}$ are given in pm and χ_e in eV.

λ, nm	χ_e	g_{eff}	RV_{max}	W_V	W_I	$P_{H,V}$	$P_{T,V}$	$PW_{H,V}$	$PW_{T,V}$	$PW_{H,I}$	$PW_{T,I}$
477.00 C I	7.48	1.5	0.043	0.61	1.26	0.025	0.625	0.48	9.0	0.04	3.0
477.59 C I	7.49	2.0	0.053	0.84	1.47	0.015	0.769	0.53	12.6	0.08	3.7
538.00 C I	7.68	1.0	0.057	0.91	2.57	0.048	0.876	0.84	14.0	0.19	4.8
612.62 Ti I	1.07	1.2	0.126	1.63	2.17	0.006	-2.210	0.63	-28.2	0.13	-40.2
612.89 Ni I	1.68	1.5	0.155	1.98	2.45	-0.055	-0.055	0.47	-27.9	0.14	-38.3
611.16 V I	1.04	1.3	0.080	0.90	1.11	0.033	-1.420	0.14	-15.5	0.07	-21.2
524.75 Cr I	0.96	2.5	0.379	5.84	9.02	0.470	-6.415	5.65	-93.2	4.06	-138.0
570.84 Si I	4.95	1.5	0.222	4.26	9.47	0.269	-0.839	4.56	-9.6	3.15	-46.8
523.46 Fe II	3.22	0.9	0.285	2.88	8.93	0.648	3.350	5.67	32.3	5.16	6.4
532.55 Fe II	3.22	1.1	0.200	2.28	4.11	0.121	1.670	1.91	19.1	1.21	5.7
541.41 Fe II	3.22	1.2	0.126	1.48	2.65	0.040	0.880	0.81	10.7	0.13	3.4
614.99 Fe II	3.89	1.3	0.219	2.93	4.17	0.060	2.252	1.85	29.8	1.08	10.9
636.94 Fe II	2.89	2.1	0.133	1.74	2.09	0.007	0.846	-0.12	11.3	-0.17	2.3
480.81 Fe I	3.25	1.3	0.218	1.93	2.76	0.032	-2.700	1.06	-23.6	0.31	-37.3
523.29 Fe I	2.93	1.3	0.331	3.91	10.34	1.060	-3.610	9.22	-43.5	8.70	-79.8
524.70 Fe I	0.09	2.0	0.369	5.07	7.31	0.418	-7.570	3.94	-101.0	2.86	-129.0
525.02 Fe I	0.12	3.0	0.387	5.87	8.49	0.288	-7.970	1.45	-109.0	1.18	-145.0
525.06 Fe I	2.20	1.5	0.352	4.42	11.57	1.334	-4.480	12.30	-56.8	11.60	-93.8
550.14 Fe I	0.95	1.9	0.302	5.46	14.77	0.118	-5.720	18.70	-75.1	17.80	-125.0
550.67 Fe I	0.99	2.0	0.370	6.14	16.64	0.772	-7.230	20.90	-75.5	19.60	-119.7
609.36 Fe I	4.61	1.2	0.177	2.15	3.11	0.065	-1.630	1.17	-2.0	0.41	-37.1
609.37 Fe I	4.65	1.0	0.124	1.36	2.03	0.020	-1.170	0.75	-12.8	0.14	-24.8
609.66 Fe I	3.98	1.5	0.198	3.11	4.29	-0.025	-2.080	1.66	-32.1	0.89	-85.5
615.16 Fe I	2.18	1.8	0.282	4.16	5.39	-0.025	-4.240	1.32	-61.8	0.86	-85.5
617.33 Fe I	2.22	2.5	0.334	5.92	8.23	0.103	-4.880	16.70	-80.0	0.96	-120.0
630.25 Fe I	3.69	2.5	0.334	6.77	11.02	0.131	-3.400	5.63	-61.8	3.78	-125.0
630.34 Fe I	4.32	1.5	0.032	3.75	0.46	-0.016	-0.346	0.04	-3.9	-0.10	-7.0
643.08 Fe I	2.18	1.2	0.314	4.95	13.29	1.098	-4.270	13.90	-63.3	13.10	-107.0
673.31 Fe I	4.62	2.5	0.161	2.39	2.92	-0.036	-1.520	-0.21	-22.0	-0.297	-38.3

5 Conclusion

Response functions are a fine means for the interpretation of observed Stokes profiles. They allow a reliable determination of the depth of atmospheric layers where any Stokes profile is disturbed by a disturbance in the temperature, pressure, velocity, and magnetic field. We can find the sensitivity of the profiles to fluctuations at any depth in the atmosphere, obtain quantitative sensitivity estimates which simplify the analysis of profile sensitivity.

Being used in the spectral analysis, the sensitivity indicators, which are the net response of all atmospheric layers where the line is formed to changes in one of atmospheric parameters, allowed us to analyze quantitatively the sensitivity of Stokes profiles by the example of iron lines. We made the following conclusions.

The sensitivity of the Stokes I profiles of photospheric lines to temperature, pressure,

Table 3. The changes in the maximum value of RV, in the V profile area W_V, and in the equivalent width W_I, which would occur when the magnetic intensity increases by 5% and the temperature increases by 2%.

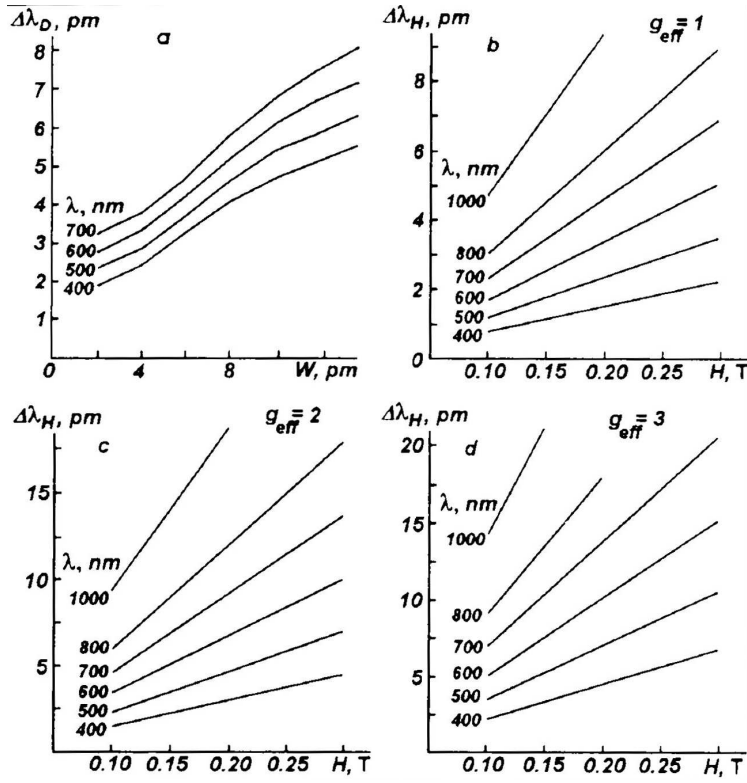| λ, nm	g_{eff}	χ_e, eV	ΔRV_H	ΔRV_T	$\Delta W_{H,V}$, pm	$\Delta W_{T,V}$, pm	$\Delta W_{H,I}$, pm	$\Delta W_{T,I}$, pm
525.02	3.0	0.12	0.014	-0.159	0.072	-2.180	0.059	-2.580
525.06	1.5	2.20	0.067	-0.090	0.615	-1.136	0.580	-1.876
614.92	1.3	3.89	0.003	0.045	0.092	0.596	0.054	0.218

Fig. 8. Plots for the determination of magnetic field conditions for the Fe I lines: a) half-width $\Delta\lambda_D$ v. equivalent width for lines not distorted by magnetic field. Magnetic broadening $\Delta\lambda_H$ v. magnetic intensity H for different wavelengths and effective Landé factors: b) $g_{\text{eff}} = 1$, c) $g_{\text{eff}} = 2$, d) $g_{\text{eff}} = 3$.

and microturbulent velocity is generally the same as for the line profiles in the absence of magnetic field [9]. The magnetic sensitivity of the Stokes V profiles is principally determined by the magnetic field conditions. The V profiles are not sensitive to magnetic field variations under the strong-field conditions ($\Delta\lambda_H \gg \Delta\lambda_D$). They become sensitive under the intermediate ($\Delta\lambda_H \approx \Delta\lambda_D$) and weak ($\Delta\lambda_H \ll \Delta\lambda_D$) field conditions. Under specific field conditions, the sensitivity of V profiles will be the strongest in lines with large wavelengths, large effective Landé factors, large equivalent widths in media with a high magnetic intensity. To make the temperature effect, which depresses the magnetic sensitivity, less pronounced, we have to take into account the effective excitation potential and to select lines with high excitation and ionization potentials. Just these lines reveal an anomalous temperature sensitivity of their V profiles — the depression grows with T rather than decreases. Chemical elements like Si I, Fe II, O I, C I may have such lines.

Sensitivity indicator tables calculated for individual lines may be useful in forming line pairs that are often used in the diagnostics of temperature and magnetic stratification inside magnetic tubes. Sometimes it is necessary to select a line with a predominant temperature or magnetic sensitivity. In this case it is desirable to have tables of sensitivity indicators for every kind of atmospheric parameters which affect the profiles and for a large number of spectral lines. Thus it would be possible to find a line sensitive to one parameter and insensitive to other parameters.

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